

A wavy twisted neutral sheet observed by CLUSTER

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[1] From July to October 2001, the Cluster satellites were located within the magnetotail and crossings of the neutral sheet were frequently observed by the FGM instrument [Balogh *et al.*, 2001]. The neutral sheet often appears to be moving relative to the spacecraft. Multiple crossings of the neutral sheet on August 3, 2001 are analysed. These neutral sheet crossings were rather unusual. Spacecraft 2, which is in the northwestern part of the Cluster tetrahedron, leads the crossing from the north to the south lobe which implies a strongly twisted magnetotail on a local scale. Examining the solar wind interplanetary magnetic field conditions, we postulate that a wavy motion in the dawn-dusk direction is superimposed on an extremely twisted and warped neutral sheet. **INDEX TERMS:** 2744 Magnetospheric Physics: Magnetotail; 2708 Magnetospheric Physics: Current systems (2409); 2764 Magnetospheric Physics: Plasma sheet. **Citation:** Zhang, T. L., W. Baumjohann, R. Nakamura, A. Balogh, and K.-H. Glassmeier, A wavy twisted neutral sheet observed by CLUSTER, *Geophys. Res. Lett.*, 29(19), 1899, doi:10.1029/2002GL015544, 2002.

1. Introduction

[2] The study of the neutral sheet is of fundamental importance in understanding the physical processes involved in the solar wind interaction with the magnetosphere, because the dynamics of the Earth's magnetosphere are greatly influenced by physical processes that occur near the neutral sheet. The neutral sheet is a relatively narrow region within the plasma sheet where the X component of the magnetic field, measured along the Sun-Earth axis, reverses sign and the magnetic field intensity reaches a minimum. This neutral sheet, also called the current sheet, separates the magnetotail into two adjacent half cylinders which have opposite magnetic field polarities. Since the first discovery of the magnetotail neutral sheet [Ness, 1965], extensive studies have been made on the average neutral sheet configuration and associated variation of the neutral sheet position with solar wind and interplanetary magnetic field conditions [Russell and Brody, 1967; Bowling and Russell, 1976; Fairfield, 1980; Cowley, 1981; Gosling *et al.*, 1986; Dandouras, 1988; Hammond *et al.*, 1994; Nakai *et al.*, 1997]. It is found that the neutral sheet is a warped

surface which crosses the solar magnetospheric equatorial plane on the flanks of the tail. The shape of this warped neutral sheet is influenced substantially by the tilt of the geomagnetic dipole relative to the solar magnetospheric Z axis. Diurnal and annual variations in the tilt angle bend the neutral sheet away from the equatorial plane.

[3] Another important effect on the shape of the neutral sheet is caused by the transverse component of the interplanetary magnetic field. Russell [1972] conjectured a twisting effect of the IMF By on the tail. Newly reconnected field lines in the plasma mantle does not align parallel to the Earth-Sun line but bend in the direction of the imposed IMF. Cowley [1981] addressed the twisting effect in the framework of a simple quantitative model of the tail field and suggested that reconnected field lines exert a torque upon the magnetotail which may twist a portion of the north lobe below the ecliptic plane and part of the south lobe above it. Sibeck *et al.* [1985] found a strong twist of the magnetotail for a strong Y component of the IMF, based on ISEE 3 data in the deep tail. The neutral sheet twists on an axis along X (or more correctly along the solar wind flow direction). The twist of the current sheet depends on the direction and strength of the IMF in the Y-Z plane, on the distance of the s/c from the Earth and on whether the IMF is north or south. Interestingly, Owen *et al.* [1995] showed that the current sheet is less twisted for southward IMF than for northward IMF, based on ISEE 3 data.

[4] In addition to the aboved mentioned warping and twisting, the neutral sheet frequently appears to be in motion due to changing solar wind conditions and geomagnetic activity. Multiple crossings of the neutral sheet by spacecraft have been attributed to a flapping motion of the neutral sheet in the north-south direction [Speiser and Ness, 1967], to a wavy profile either along the direction of the magnetotail [Speiser, 1973], or waves along the dawn-dusk direction [Lui *et al.*, 1978]. A good summary of the various signatures of neutral sheet crossings can be seen in Figure 7 of Lui [1984].

[5] From July to October 2001, the apogees of the Cluster satellites were located within the magnetotail and crossings of the neutral sheet were frequently observed by the FGM instrument. In many cases, the neutral sheet appears to move back and forth across the spacecraft several times. Hence, multiple crossings are often observed. In this paper, multiple crossings of the neutral sheet on August 3, 2001 are analysed. With four spacecraft, we determine the normal direction and the motion of the neutral sheet. We examine the

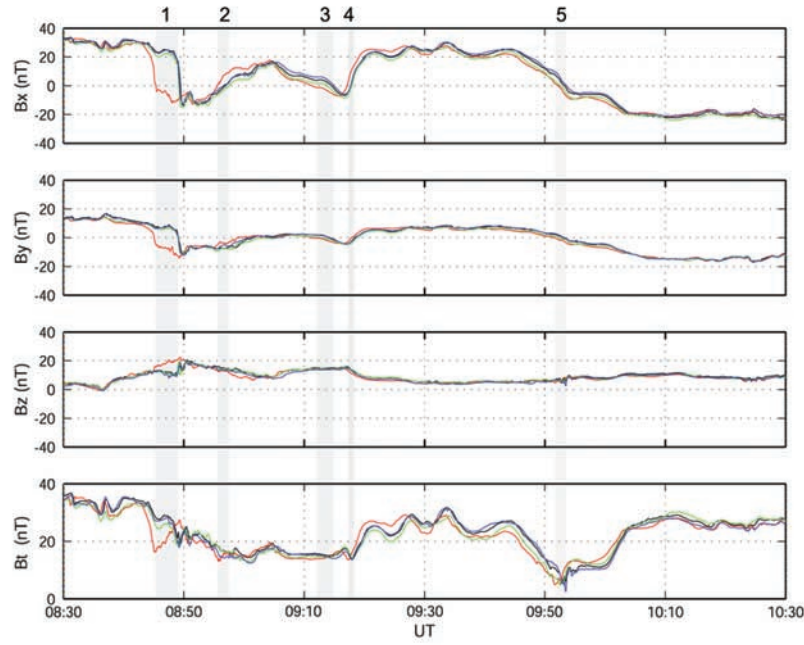


Figure 1. 4-s magnetic field data between 0830 and 1030 UT on August 3, 2001. The data are shown in GSM coordinates with a color scheme of: black, red, green, blue for spacecraft 1 to 4, respectively.

magnetic configuration of the neutral sheet. An unusual feature, a locally “reversed” magnetotail, is revealed by the observation. We argue that the observation can be explained simply by a wave moving in the dawn-dusk direction being superimposed on an extremely twisted and warped neutral sheet. We show the merit of the Cluster four spacecraft measurement in resolving an otherwise ambiguous observation.

2. Observations

[6] Figure 1 shows the magnetic field data between 0830 and 1030 UT on August 3, 2001. The data are shown in GSM Cartesian coordinates with a color scheme of black, red, green, blue for spacecraft 1 to 4, respectively. In this study, we restrict ourselves to 4-s spin average data. In Figure 1, all spacecraft are located initially in the north lobe indicated by $B_x > 0$. Starting with the first crossing at ~ 0847 UT, there are five crossings of neutral sheet in about one hour, indicated in the plot by shaded regions. The numbers at the top of the shaded areas indicate the crossing sequence. All crossings, except crossing 3, satisfy the common definition of neutral sheet, i.e., the $B_x = 0$ and the magnetic field intensity reaches a minimum. For crossing 3, the crossing of neutral sheet has been identified only by the change of $B_x > 0$ to $B_x < 0$. All Cluster spacecraft measure similar magnetic profiles during the interval, except around the first neutral sheet crossing. At 08:45:26 UT, s/c 2 crossed the neutral sheet from north lobe to south lobe. About 4 minutes later the other three spacecraft crossed the neutral sheet with the sequence of s/c 3, s/c 4, s/c 1 at 08:49:10, 08:49:18, and 08:49:26 UT, respectively. For better understanding the time sequence of the neutral sheet crossing, we show in Figure 2 the Cluster tetrahedron configuration at 0847 UT. The positions of the spacecraft are relative to s/c 3, which was at a GSM position of

$(-16.9, -8.7, 3.2)$ Re for the first crossing around 0847 UT. The Cluster tetrahedron moves slowly in the $-Z$ direction. At 0952 UT, the time of the fifth crossing, s/c 3 was at $(-16.9, -8.6, 2.7)$ Re. The relative positions of the spacecraft in the tetrahedron remain unchanged during the observations reported here. With such a Cluster configuration, s/c 3 is most likely to lead during north–south crossings of the neutral sheet. Now we go back to Figure 1 and we note that crossings 1, 3, 5 exhibit an unusual phenomenon, i.e., s/c 2 leads the crossings from the $B_x > 0$ hemisphere to the $B_x < 0$ hemisphere. From the tetrahedron geometry of the Figure 2, one can see easily that the lead of s/c 2 during a $B_x > 0$ hemisphere to $B_x < 0$ hemisphere crossing implies a very steeply inclined neutral sheet.

[7] To put our observation on a more quantitative basis, we determine the neutral sheet orientation and speed along the neutral sheet normal. Using measurements at four non-coplanar and well separated spacecraft, the orientation and

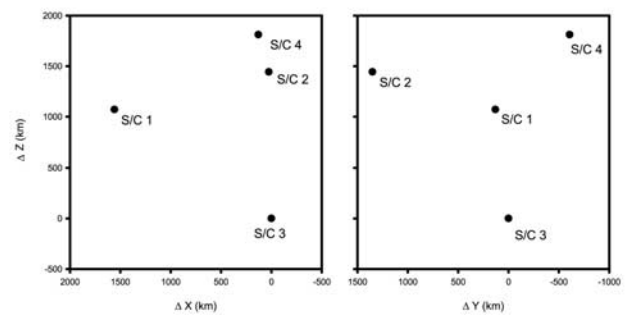


Figure 2. Tetrahedron shape and relative position of the Cluster spacecraft at 0847 UT. Spacecraft 3 was at a GSM (X, Y, Z) position of $(-16.9, -8.7, 3.2)$ Re.

Table 1. Neutral sheet crossings at August 3, 2001

Crossing	Time	Normal direction	Speed (km/s)	Deviation angle
1	0847	0.346, -0.890, -0.296	7.1	107
2	0857	0.230, -0.608, -0.760	16.9	41
3	0912	0.340, -0.940, -0.014	8.4	91
4	0917	0.127, -0.841, -0.526	39.9	58
5	0952	0.317, -0.848, 0.425	20.8	65

velocity can be determined uniquely. We first find out the times and locations of the neutral sheet crossing, i.e., $B_x = 0$, by all four spacecraft. Then with four times and four position vectors, the normal of the neutral sheet and the speed along the normal can be calculated. Here we assume the neutral sheet speed is constant over the region including the observations and the neutral sheet is planar over the separation scale of the spacecraft. We note that possible errors for these assumptions may arise due to curvature of the discontinuity, acceleration of the surface.

[8] Table 1 lists the normals and speeds along the normal direction of the neutral sheet. For convenience, we define a neutral sheet deviation angle as the angle of deviation of the neutral sheet from the ecliptic plane in GSM coordinate to describe a localized neutral sheet normal variation. We avoid to use terms such as tilt angle or twist angle. The tilt angle normally describes the tilt of the neutral sheet around the Y axis in the near tail, while the twist angle is around the X axis due to the global twisting of the IMF B_y effect. Of the five multiple crossings of neutral sheet, we find two cases with a deviation angle of more than 90° . The remaining three crossings also exhibit deviation angle between 41° and 65° , the neutral sheet thus exhibits a consistently steep appearance.

3. Discussions

[9] A larger than 90° deviation angle (for example, the 0847 UT crossing) indicates an upside-down magnetotail, i.e., the north lobe is located in southward of the south lobe, in the same sense as observed by *Sibeck et al.* [1985]. However, there are some differences between our observation and their observation. Sibeck et al. found their reversed lobe case in the deep tail, where the tail field is directly

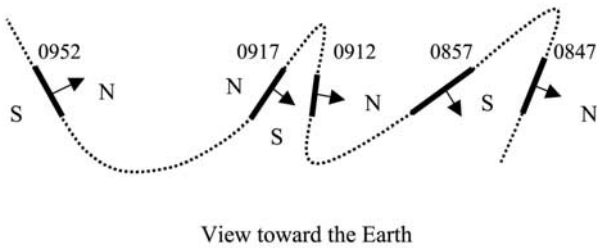


Figure 3. Schematic illustration of the motion of the neutral sheet determined from each individual crossing in the GSM Y - Z plane. The moving direction the neutral sheet is shown with arrows. N and S indicate the $B_x > 0$ hemisphere and the $B_x < 0$ hemisphere of the magnetotail lobes, respectively. The dotted line is a simple connection of the all the neutral sheet orientations at different times.

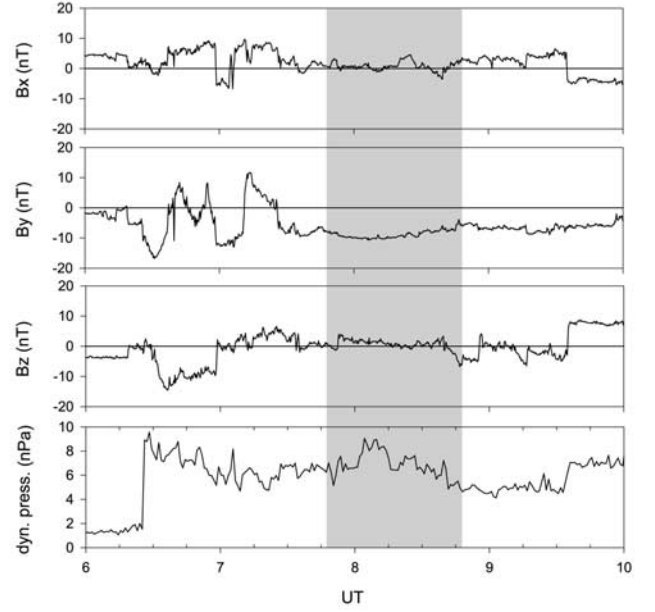


Figure 4. IMF and solar wind conditions recorded by ACE. The shaded region indicates the interval from crossing 1 to crossing 2. The delay time between ACE and the Earth is about 60 minutes.

connected with IMF. Thus a global twist of the magnetotail is possible. In our case, Cluster is located about 17 Re tailward, a global reversal of the magnetotail is unlikely in the near Earth tail. In addition, we note that after the 0847 UT reversal crossing, a normal crossing followed at 0857 UT, then at 0912 UT, another reversal crossing occurs. The sequence of the crossings suggests a wavy profile in the neutral sheet.

[10] In Figure 3, we illustrate schematically the motion of the neutral sheet determined from each individual crossing in the Y - Z plane. N and S indicates $B_x > 0$ hemisphere and $B_x < 0$ hemisphere of the magnetotail lobes, respectively. The directions of the current sheet motion all point to the dawn side. These observations can be explained by a wave moving across the tail from midnight to dawn. By simply connecting the neutral sheet configuration observed from each individual crossing with dotted lines in Figure 3, we see that a wavy profile of the neutral sheet along the dawn - dusk direction can explain the multiple crossings easily. However, very sharp bends, such as between crossing 1 and 2, or between crossing 3 and 4, in the neutral sheet are evidently unlikely.

[11] The large deviation angle of the neutral sheet in these observations may arise from several effects. First we note that the spacecraft are located at dawn side of the flank at about 9 Re in -Y direction, where the warping effect might bend the neutral sheet away from the GSM ecliptic plane. The tilt angle of the geomagnetic dipole is only about 10° sunward during this period. Using *Fairfield* [1980] neutral sheet model, we can determine the orientation of the neutral sheet due to dipole tilt effect at 8.7 Re in -Y direction at this time. The warping effect would cause the neutral sheet 4° tilting toward the dawn at this location. Since the warping effect may not be strong enough to explain our observations, we examine the IMF B_y effect next.

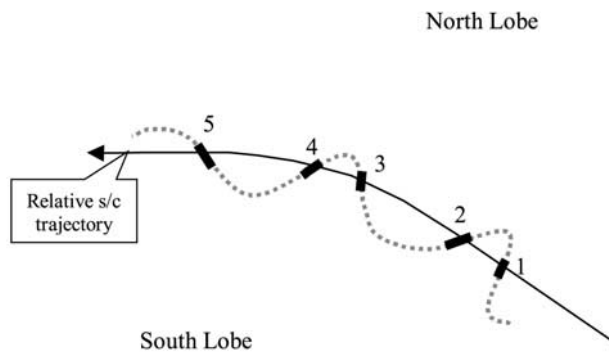


Figure 5. Schematic interpretation of the multiple crossings between 0847 – 0952 UT. View toward the Earth. A wave moving in the dawn-dusk direction is superimposed on an extremely twisted and warped neutral sheet. The numbers indicate the crossings of the neutral sheet by the spacecraft.

[12] Solar wind conditions are shown in Figure 4, from top to bottom are the IMF B_x , B_y , B_z components in GSM coordinates and the solar wind dynamic pressure, all measured by ACE between 0500 and 1100 UT, 245 Re upstream and 14 Re dawnward of the Earth. The magnetic field measurements have 16 s resolution and the plasma data has 64 s resolution. At 0627 UT, an interplanetary shock arrived at ACE. Following the shock, IMF B_y was strongly enhanced and switched directions between positive and negative several times until 0725 UT. After 0725 UT, IMF B_y remained strongly negative for several hours, including the interval of this study. Since the solar wind velocity (not shown here) was relatively quiet at around 430 km/s after the shock, we can estimate the solar wind convection time from ACE to the Earth being approximately 60 minutes. Considering this delay time between ACE and the Earth, we find the first crossing of the neutral sheet in this study occurred 80 minutes after the shock arrived the Earth. During the interval in this study, IMF B_y was strongly negative, B_x was weak and variable, B_z was mainly northward. Thus the magnetotail is subject to the IMF B_y twisting effect [Cowley, 1981; Ashour-Abdalla et al., 1998]. This IMF B_y twisting effect could tilt the neutral sheet flank strongly dawnward in the same sense as the dipole warping effect at the location of our observations [Ashour-Abdalla et al., 1998].

[13] We illustrate in Figure 5 a possible explanation of the multiple neutral sheet crossing observations. A wave moving in the dawn-dusk direction is superimposed on an extremely twisted warping neutral sheet. By taking a wave propagation velocity of ~ 20 km/s and a wave period of ~ 20 minutes, we estimate that the wavelength is about 4 Re. The cause of the local “reversal” can easily be understood from Figure 5. The “reversal” of the tail is a local phenomenon caused by a wave, very different to the global reversal of the lobes observed by ISEE 3 in distant tail [Sibeck et al., 1985].

[14] We have surveyed all the Cluster magnetotail neutral sheet crossings between July 15 and October 15. We find that s/c 3 takes the lead during the north lobe to south lobe

crossing for most of the time. Only few cases have been found for the s/c 2 leading the neutral sheet crossing from $B_x > 0$ hemisphere to $B_x < 0$ hemisphere. A further study is underway on this very steeply inclined neutral sheet.

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